Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources

George W. Kattawar
Dept. of Physics
Texas A&M University
College Station, TX   77843-4242
phone: (409) 845-1180   fax: (409) 845-2590   e-mail: kattawar@tamu.edu

LONG-TERM GOALS

Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the inherent optical properties (IOP's) of both oceanic and littoral zone constituents. We also want to explore the efficacy of polarimetric time-of-flight lidar techniques in determining salinity and speed of sound in the ocean as well as submersible object detection. We are also working on a new instrument design to measure simultaneously both the scattering and absorption coefficients of ocean water. We want to continue our collaborative program in ocean and atmospheric polarimetry with the group in Minsk headed by Dr. Eleonora Zege.

OBJECTIVES

It is our major objective to find new and innovative ways in which polarimetry can be used to determine not only IOP's but also certain physical properties such as temperature and salinity of ocean water. We also want to further develop a new method of imaging which we would like to label "Mueller matrix imaging" (MMI). With this method we want to determine how much more information we can obtain about target features by using elements other than S_{11} (ordinary radiance) of the Mueller matrix We will continue feasibility studies for a new scattering and absorption meter to simultaneously measure both the scattering and absorption coefficient for ocean water samples .

We wish to continue our collaborative program with the Radiative transfer group in Minsk, Belarus headed by Dr. Eleonora Zege. Our new objectives for this program are as follows:

a) Rigorously compare the addition of a Lambert bottom surface as well as a stochastic interface between the Multi-component Approach (MCA) and the Monte Carlo approach with full Mueller matrix formulation.
b). Development of the simplified equations for propagation of a linearly polarized beam in order to study the Stokes vector in the on-axis region for both backward and forward directions.
c) Development of the code to compute the Stokes vector in the on-axis region for a polarized narrow beam and compare with experimental data.
d) Extending the techniques we have developed for detection and characterization of both organic and inorganic atmospheric aerosols

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**
4. TITLE AND SUBTITLE **Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dept. of Physics,,Texas A&M University,,College Station,,TX, 77843**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the inherent optical properties (IOP???s) of both oceanic and littoral zone constituents. We also want to explore the efficacy of polarimetric time-of-flight lidar techniques in determining salinity and speed of sound in the ocean as well as submersible object detection. We are also working on a new instrument design to measure simultaneously both the scattering and absorption coefficients of ocean water. We want to continue our collaborative program in ocean and atmospheric polarimetry with the group in Minsk headed by Dr. Eleonora Zege.

15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

APPROACH

We have developed some very sophisticated Monte Carlo codes to handle the following types of problems:

a) Complete Mueller matrix calculations for a passive source (the sun) illuminating a plane parallel inhomogeneous atmosphere-ocean system with a wind ruffled dielectric interface. This program uses a new statistical estimation technique that allows for the multiple scattering Mueller matrix to be computed at precise angles without any solid angle averaging. We have also developed a new technique to handle a Lambertian bottom so that all bottom albedos can be computed in a single run. This work is being done by Hatcher Tynes, who has recently completed his Ph.D.on this project.
b) We have also developed a new Monte Carlo program to calculate the multiple scattered Mueller matrix from a target embedded in a turbid medium. This program uses state-of-the-art estimation techniques to improve the statistics over conventional "brute force" methods. It also utilizes any symmetry properties of the target. The single scattered Mueller matrix for the target is a sine qua non for these calculations. This work is being carried out by Deric Gray who is a doctoral student working on this project.

WORK COMPLETED

a) One phase of our collaborative work with Dr. Zege's group in Minsk has been completed which involved a comparison of her multi-component approach method with our Monte Carlo models for a coupled atmosphere-ocean system with an interface with no wind ruffling using a Henyey Greenstein volume scattering function. We have made the first comparisons of the strong ellipticity encountered underneath the interface of the ocean surface. The results of this study have recently appeared in Applied Optics.[1] .
b) We have completed a study of the efficacy of using certain polarimetric signatures to detect targets at optical depths where ordinary radiance imaging fails to resolve them. The manuscript for this interesting work is in preparation and will be submitted to Applied Optics.
c) We have also completed the addition of the stochastic interface and Lambertian bottom to our effective Mueller matrix Monte Carlo Code.

RESULTS

We were able to show (see Fig. 1) that our new statistical estimation scheme could easily accommodate a wind ruffled interface. To check our results we did a comparison with the HYDROLIGHT code of Curtis Mobley. In Fig. 1 we show a comparison between the two where scattering in both layers is totally conservative and is described by the Rayleigh scattering law. The wind speed is 5 meters per second. The atmosphere has an optical thickness of 0.01 and the ocean has an optical thickness of 1.0. Sunlight is incident at the top of the system, in the direction of the +z axis, which is taken to be vertically down. Wind ruffling is accounted for using the statistical model developed by Cox and Munk. Below the interface, the most noticeable effect of the wind ruffling is to blur the boundaries of the so-called light cone (the cone that is defined by the critical angle). As can be seen from the figure the agreement is quite good.

In Fig. 2. We show a plot of the radiance and degree of polarization (DOP)=$\sqrt{Q^2 + U^2 + V^2}$ /I for a circular disk embedded in a scattering medium. The disk is at a depth of 4 mean free paths (m.f.p.) away from a collimated source and is a Lambertian reflector with an albedo of 0.025, but with annular

regions of differing Mueller matrix elements affecting the polarization properties. 1. Polarization preserving $\mathbf{M} = \mathrm{diag}(1,1,1,1)$ 2. Depolarizing $\mathbf{M} = \mathrm{diag}(1,0,0,0)$ 3. Painted surface $\mathbf{M} = \mathrm{diag}(1,0.61,-0.58,-0.51)$ The plot shows the radiance and degree of polarization at a detector, located at the same position as the source, for three different input states of polarization of the incident beam relative to a fixed set of axes. What is extremely interesting is that normal radiance detection would not find the target; however, by using a single quantity such as the degree of polarization (DOP) we can not only "see" a hidden target but also make out its surface features when using this quantity as an imaging tool and more especially when the incident beam is right circularly polarized.

IMPACT/APPLICATION

We are now quite certain that Mueller matrix imaging, will become a standard tool for remotely sensing the atmosphere-ocean system as well as an aid in the detection of certain types of cancers.

We also believe that it will lead to better and more comprehensive target detection in turbid media. What is desperately needed in all MMI work is the single scattered Mueller matrix for the types of targets one is trying to detect.

Our Monte Carlo programs for laser scattering from turbid media are presently being used to study light scattering from living tissue. We are now working in collaboration with Dr. Ping Yang to expand his FDTD code to handle biolological samples so we can compute from first principles the single scattered Mueller matrix of anthrax spores.

Another very significant application of MMI is the detection of biological aerosols dispersed in the atmosphere.

TRANSITIONS

Our Monte Carlo passive source Stokes vector programs are being used to check a different method for solving the equations of transfer with full Stokes vector treatment developed by Dr. Eleonora Zege and her group in Minsk, Belarus. We are presently checking the addition of a Lambertian bottom as well as a stochastic interface to both our codes. Some of this work was supported by a CRDF grant.

downwelling str

windspeed = 5 m/s

$\tau_{air} = 0.01$ $\tau_{ocean} = 1.0$

$\mu_0 = 1.0$

upwelling str

1.0E+00

1.0E-01

1.0E-02

-1.0E+00 -5.0E-01 0.0E+00 5.0E-01 1.0E+00

μ

- ─ ✳ ─ Hydrolight (above surface)
- ─□─ Hydrolight (tau = 0.1)
- ─○─ Hydrolight (tau = 0.3)
- ─◇─ Hydrolight (tau = 0.8)
- ─△─ Hydrolight (bottom)
- ─■─ Estimation M.C. (above)
- ─▲─ Estimation M.C. (tau)
- ─◆─ Estimation M.C. (tau)
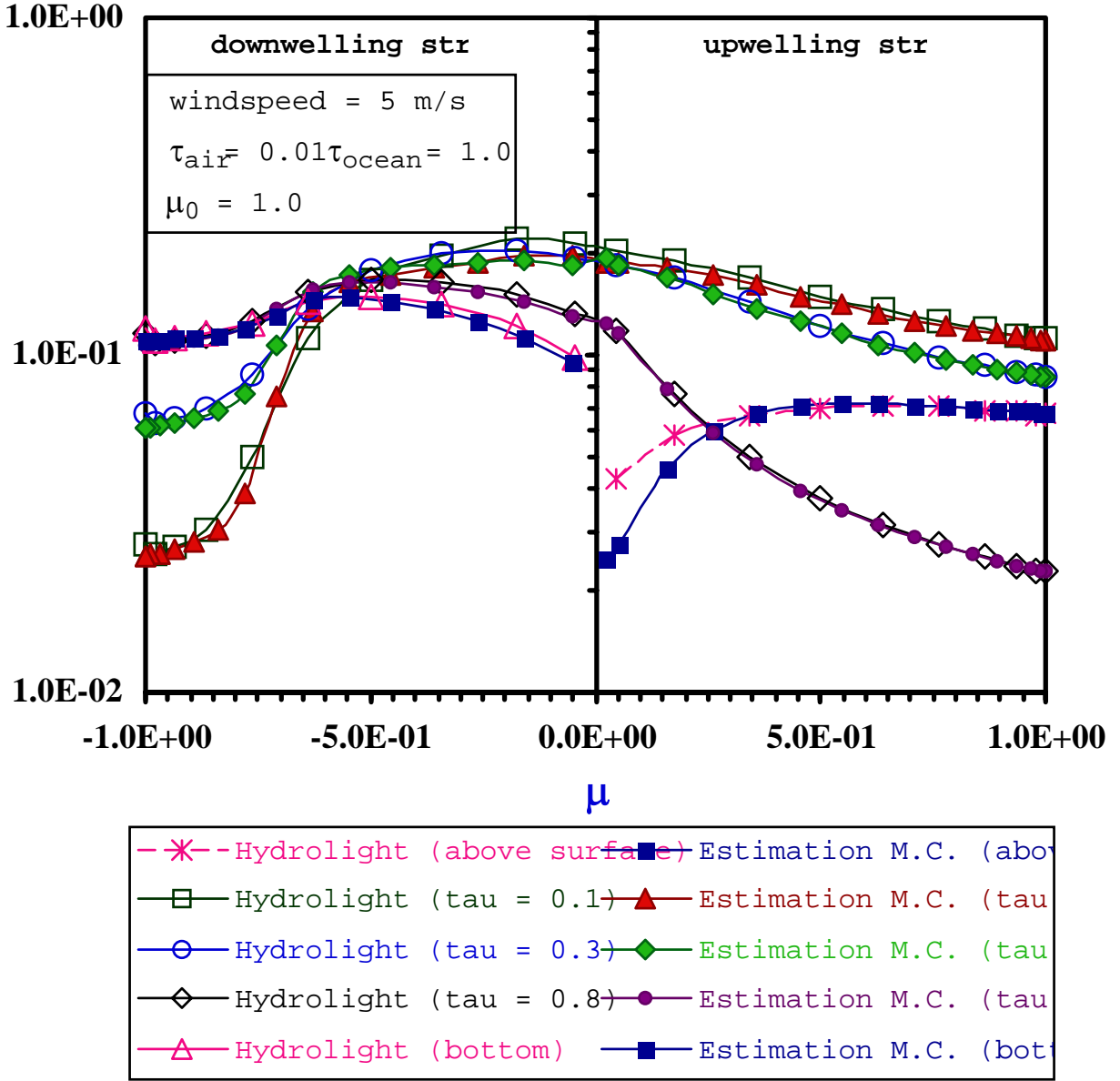- ─●─ Estimation M.C. (tau)
- ─■─ Estimation M.C. (bottom)

Fig. 1 The scalar radiance (radiance calculated without including polarization effects) for an atmosphere-ocean system with wind ruffling effects included. Scattering in both layers is totally conservative and is described by the Rayleigh scattering law. The wind speed is 5 meters per second. The atmosphere has an optical thickness of 0.01 and the ocean has an optical thickness of 1.0. Sunlight is incident at the top of the system, in the direction of the +z axis, which is taken to be vertically down. Data are compared between our estimation Monte Carlo technique and the HYDROLIGHT code developed by Curtis D. Mobley. Wind ruffling is accounted for using the statistical model developed by Cox and Munk. Below the interface, the most noticeable effect of the wind ruffling is to blur the boundaries of the so-called light cone (the cone that is defined by the critical angle).
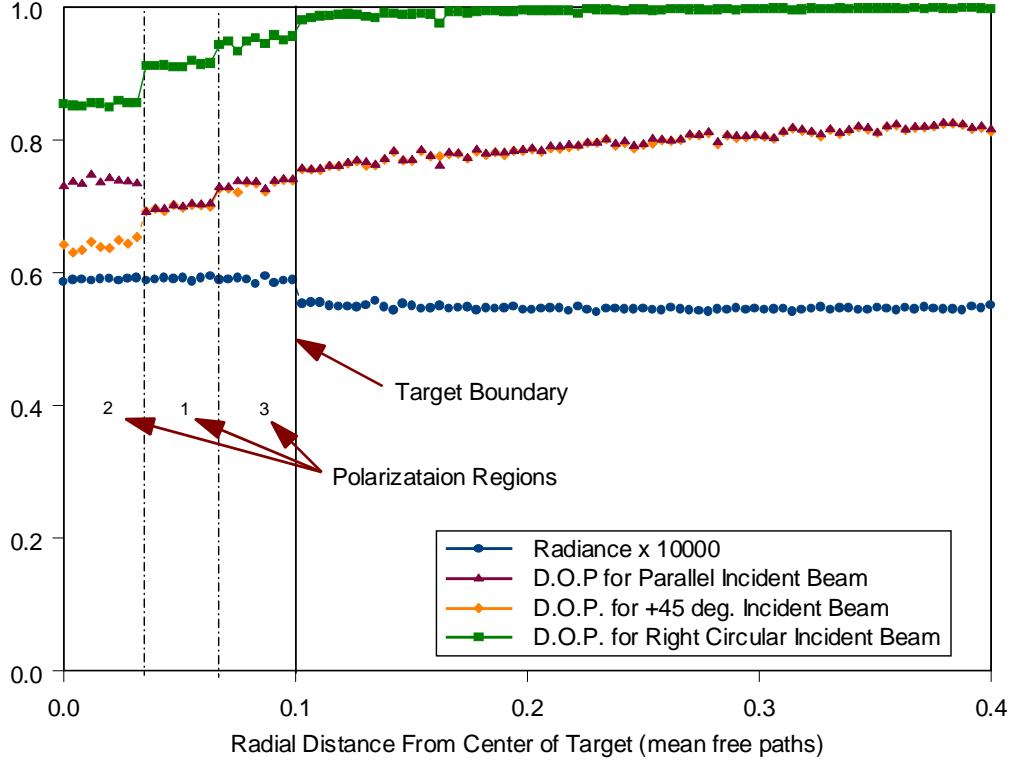
4

Fig.2 Plot of the radiance and degree of polarization (DOP) for a circular disk embedded in a scattering medium. The disk is at a depth of 4 mean free paths (m.f.p.) away from a collimated source and is a Lambertian reflector with an albedo of 0.025, but with annular regions of differing Mueller matrix elements affecting the polarization properties. 1. Polarization preserving M = diag(1,1,1,1) 2. Depolarizing M = diag(1,0,0,0) 3. Painted surface M = diag(1,0.61,-0.58,-0.51) The plot shows the radiance and degree of polarization at a detector, located at the same position as the source, for three different input states of polarization of the incident beam relative to a fixed set of axes.

RELATED PROJECTS

Our inelastic scattering code is being used in a joint project with Dr. E. S. Fry to study the feasibility of using Brillouin scattering to measure the speed of sound as a function of depth in the ocean. This project is funded by the Texas Advanced Technology Program.

We have also used our time-of-flight Monte Carlo code to check the validity of the small angle approximation in the solution of the radiative transfer equations. We have collaborated on some of these issues with Dr. Walt McBride of NRL Stennis.

We have also modified our Monte Carlo codes to emulate a new design for a device to simultaneously measure both the scattering and absorption coefficients for ocean water samples.

REFERENCES

1. H. Hatcher Tynes, George W. Kattawar, Eleonora P. Zege, Iosif L. Katsev, Alexander S. Prikhach, and Ludmila I. Chaikovskaya, " Monte Carlo and multicomponent approximation methods for vector radiative transfer by use of effective Mueller matrix calculations" Appl. Opt. 40, 400-412, 2001.

PUBLICATIONS

1. B. D. Joelson and G. W. Kattawar," Multiple scattering effects on the remote sensing of the speed of sound in the ocean by Brillouin scattering", Applied Optics, 35, 2693-2701, (1996)

2. J. T. Adams and G. W. Kattawar, "Neutral points in an atmosphere-ocean system.1: Upwelling light field", Appl. Opt. 36, 1976-1986, (1997)

3. M. J. Rakovic and G. W. Kattawar, "Theoretical analysis of polarization patterns from incoherent backscattering of light", Appl. Opt. 37, 3333-3338, 1998

4. B. D. Cameron, M. J. Rakovic, M. Mehrubeoglu, G. W. Kattawar, S. Rastegar, L. V. Wang, and G. L. Cote, "Measurement and Calculation of the Two-Dimensional Backscattering Mueller Matrix of a Turbid Medium" , Optics Letters, 23 , 485-487, (1998).

5 M. J. Rakovic, G. W. Kattawar, M. Mehrubeoglu, B. D. Cameron, L. V. Wang, S. Rastegar, and G. L. Cote, "Light backscattering polarization patterns from turbid media: theory and experiment," Appl. Opt. 38, 3399-3408, 1999

6. G. W. Kattawar and M. J. Rakovic " Virtues of Mueller Matrix imaging for underwater target detection" Appl. Opt.38, 6431-6438, 1999

7. H. Hatcher Tynes, George W. Kattawar, Eleonora P. Zege, Iosif L. Katsev, Alexander S. Prikhach, and Ludmila I. Chaikovskaya, " Monte Carlo and multicomponent approximations methods for vector radiative transfer by use of effective Mueller matrix calculations" Appl. Opt. 40, 400-412, 2001.

PATENTS

System and Method for Detecting Underwater Objects
U.S. Patent Appln. Serial No. 09/491,943
Inventors: Edward S. Fry, George W. Kattawar, Thomas Walther, and Xioajiang Pan